Innovative Technologies for Converters and Chargers

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Overview

Timeline

- **Start – FY14**
- **End – FY16**
- **85% complete**

Budget

- **Total project funding**
  - **DOE share – 100%**
- **Funding received in FY15: $990K**
- **Funding for FY16: $1,100K**

Barriers

- **Reducing onboard battery charger and dc-dc converter cost, weight, and volume**
- **Achieving high efficiency**
- **Overcoming limitations of present semiconductor and magnetic materials to address charger and converter cost, weight, volume and efficiency targets** (charger technical targets are being developed)

Partners

- **GaN Systems**
- **Aegis Technology Inc.**
- **Ferroxcube**
- **NREL**
- **ORNL team member:** Cliff White, Larry Seiber, Randy Wiles, Zhenxian Liang

Project Objective and Relevance

- **Overall Objective**
  - **Develop low cost, high efficiency, high power density all wide band gap (WBG) integrated dc-dc converter and on-board charger (OBC)**
  - **Goals**
    - **Cost, weight, and volume reduced by 50%;**
    - **Efficiency better than 96% (compared to state-of-the-art)**

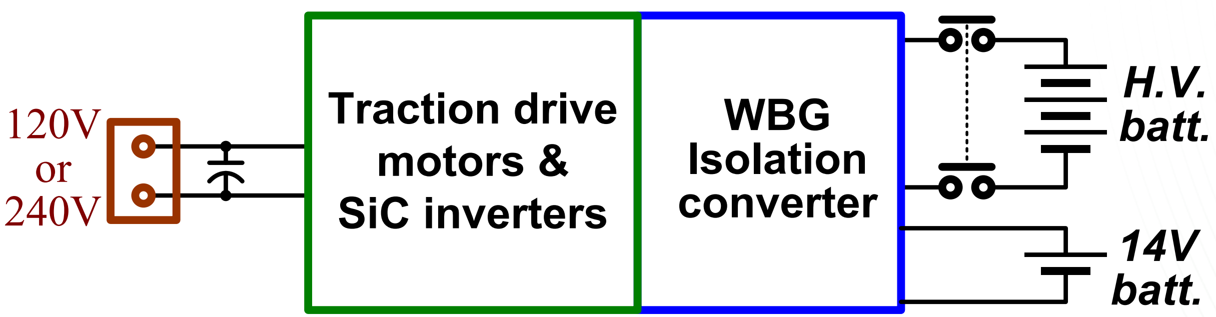
- **FY16 Objective**
  - **Design, build, and test a 6.6 kW GaN isolation converter**
  - **Integrate the 6.6 kW GaN isolation converter with a SiC traction drive for an all-WBG OBC and test and characterize the integrated OBC**

Milestones

Date	Milestones and Go/No-Go Decisions	Status
Sept. 2014	Milestone: Designed, built, and tested a 6.6 kW SiC isolation converter prototype	**Complete**
Sept. 2014	Go/No-Go decision: Prototype design indicated the integrated OBC can meet the cost, efficiency, weight, and volume goals	**Go**
March 2015	Milestone: Designed, built, and tested a 6.6 kW SiC integrated onboard charger	**Complete**
March 2016	Go/No-Go decision: If 6.6 kW GaN isolation converter design meets efficiency >98%, proceed to build a prototype and integrate into all-WBG OBC	**Go**
Sept. 2016	Milestone: Integrate the 6.6 kW GaN isolation converter with a SiC traction drive for an all-WBG OBC and test and characterize the integrated OBC	

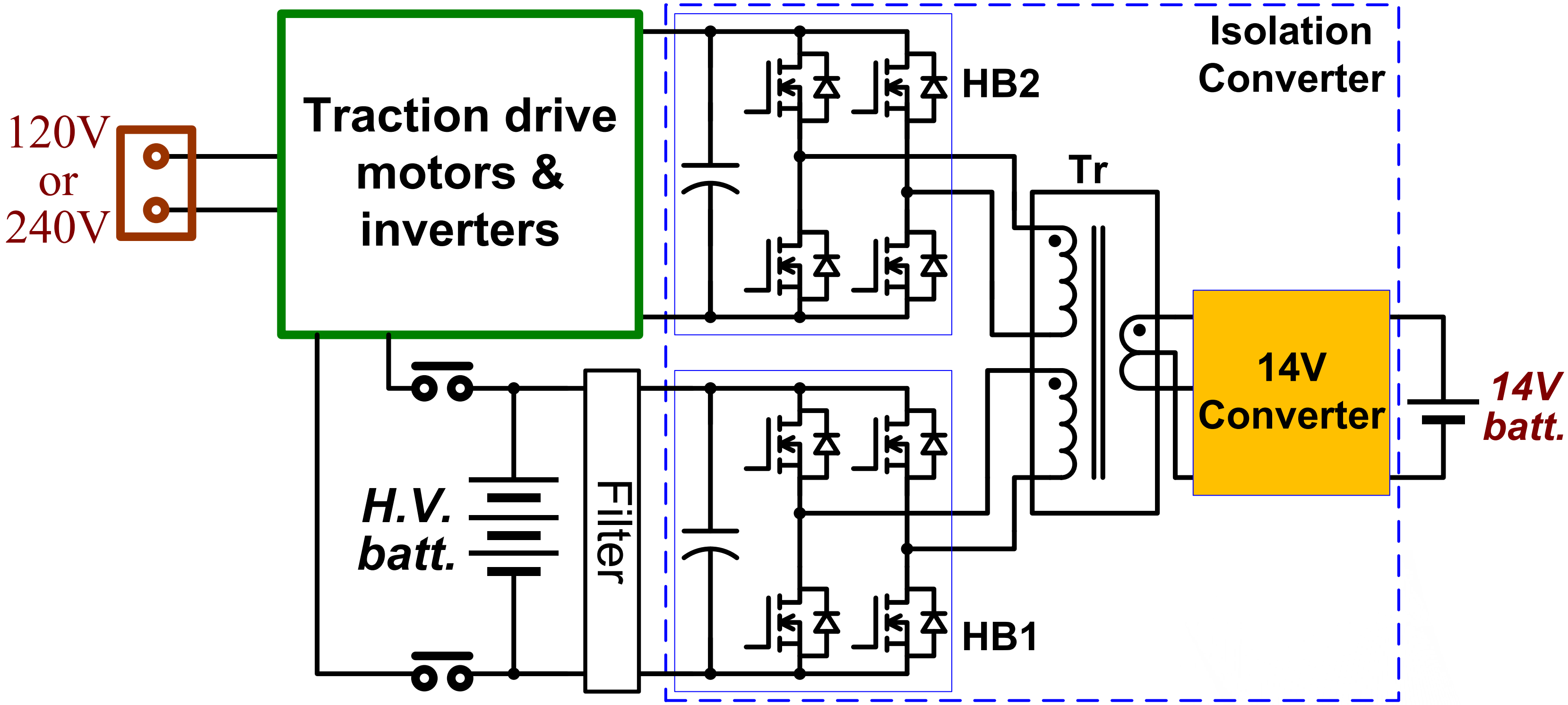
Approach
Strategy to Address Limitations of SOA

- **Develop WBG integrated onboard charger**
  - Utilize traction drive inverters and motors as part of the charger converter
  - Provide galvanic isolation
  - Provide high voltage (H.V.) to 14V battery dc-dc conversion
  - Use soft switching for electromagnetic interference (EMI) reduction and efficiency improvement
  - Develop a control strategy to reduce the bulky dc link capacitor, needed to filter out the large voltage ripple of twice the fundamental frequency
- **Aggressive pursuit of power density and specific power without compromising efficiency**
  - All WBG converter (SiC and/or GaN)
  - Advanced soft magnetic materials (Nano-composite)



Conceptual diagram of an integrated onboard charger

Approach
Strategy to Address Limitations of SOA

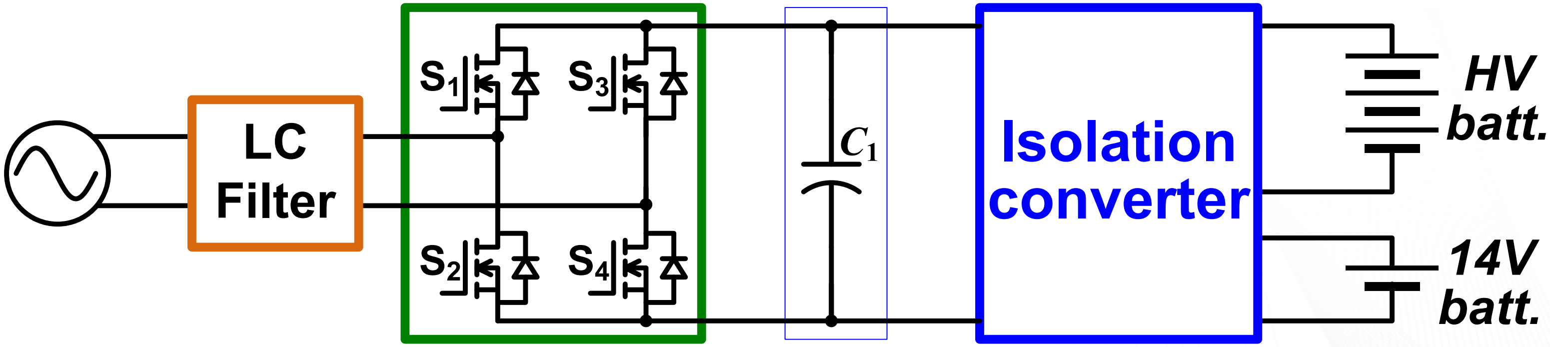


- **Using the traction drive as the OBC AC-DC front end converter**
- **3-port isolation converter**
  - Dual active H-bridge converter (soft switching, synchronous rectification)
  - Sharing converter (HB1) and transformer with the 14V battery charger
- **Bidirectional power flow**

Approach
Strategy to Address Limitations of SOA

- **Can be applied to most traction drive systems**
  - Dual inverter and motor (does not need to have same ratings)
  - Single inverter and motor with a boost converter
  - Segmented inverter traction drive (single inverter and motor)
  - Single inverter and motor without a boost converter-need to add a pair of switches or diodes

- **The isolation converter can also be applied to standalone OBCs**

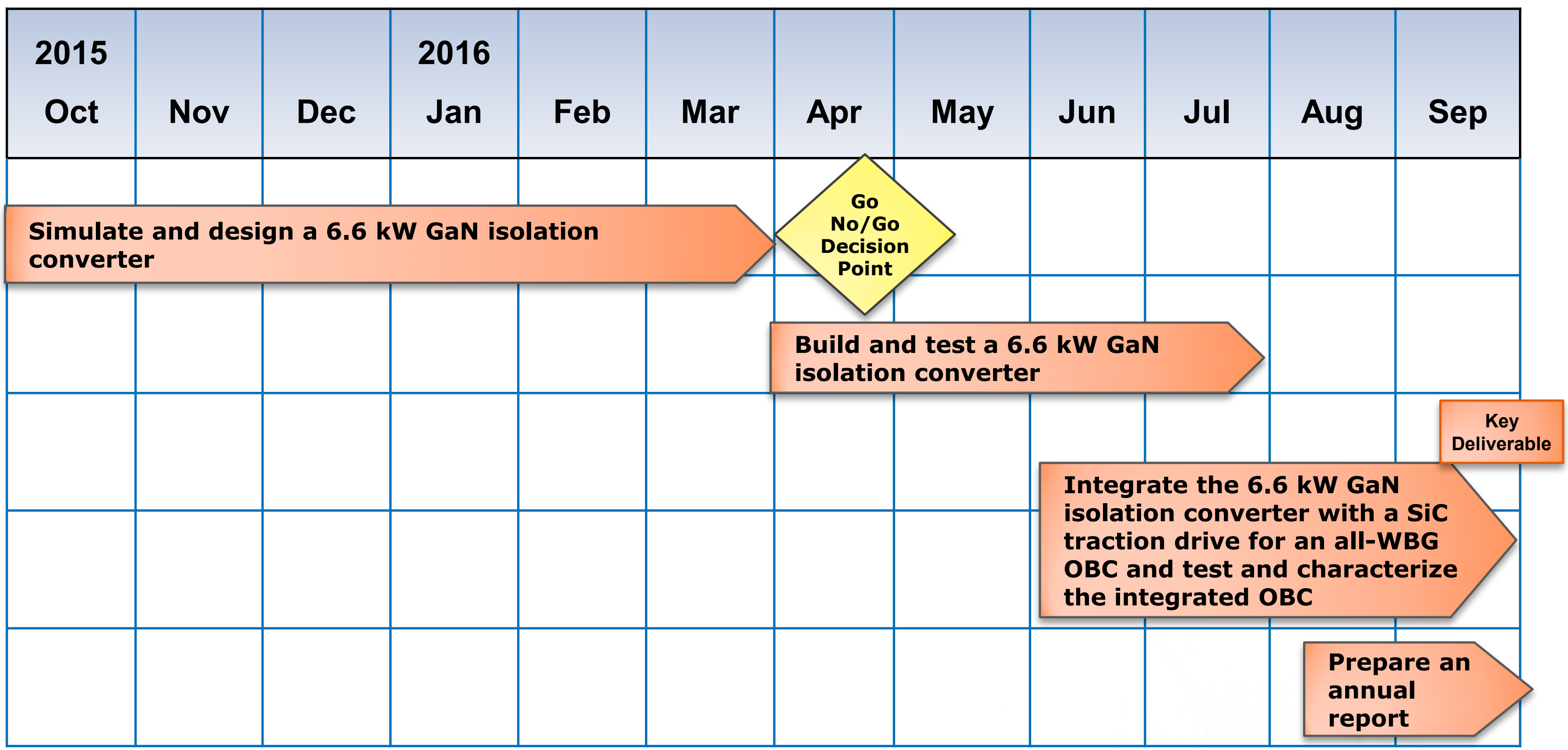


Approach is flexible and applicable to various traction drive system architectures

Approach
Strategy to Address Limitations of SOA

- **The goal of this research is to**
  - Minimize components through utilization of onboard power electronics and significantly increasing switching frequency
  - Reduce weight and volume of the dc-dc converter and charger by a factor of two
  - Increase efficiency to better than 96%, (> 40 % loss reduction compared to that of the SOA)
- **Potential to impact industry**
  - Introduction of all-WBG devices enables higher power density and higher efficiency chargers and converters
- **Uniqueness**
  - A unique charger topology that
    - minimizes the number of components through functional integration
    - is applicable to various traction drive system architectures
  - Fully utilizing the capabilities of WBG semiconductor and novel magnetic materials

Approach FY16 Timeline

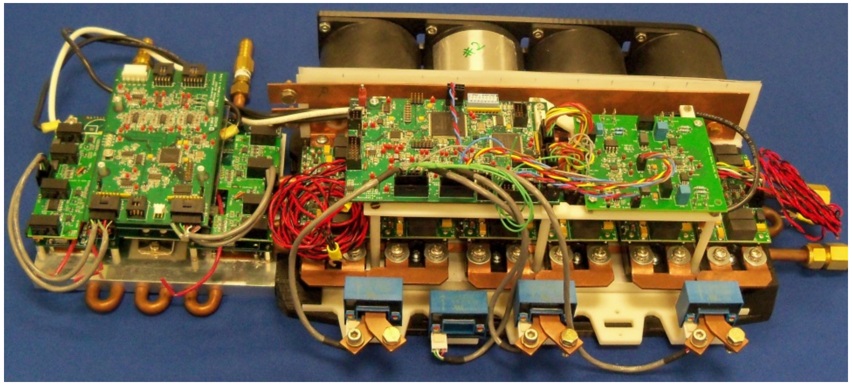


Go No/Go Decision Point: If design meets efficiency goal of 98 %, proceed to build a 6.6 kW GaN isolation converter prototype.

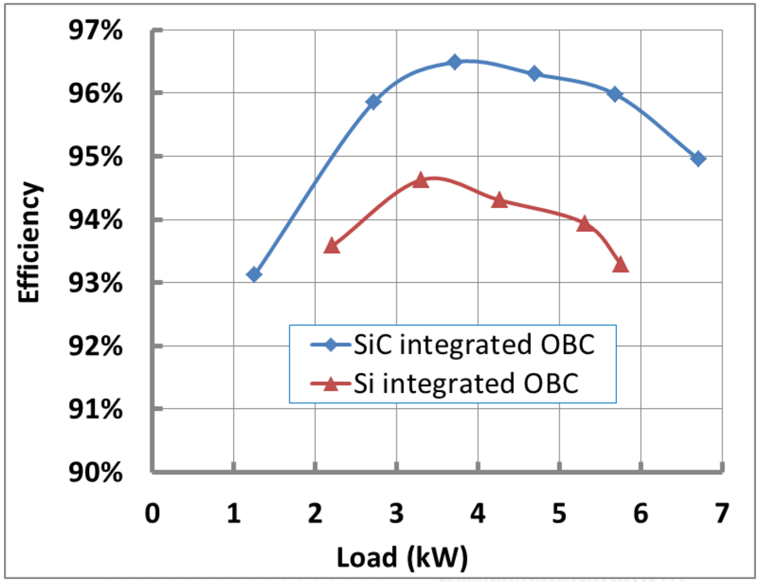
Key Deliverable: 6.6 kW WBG OBC prototype with a GaN isolation converter

Technical Accomplishments – FY15

- Designed, built, and tested a 6.6 kW SiC-based integrated OBC
  - Designed and built a SiC traction drive inverter using commercial SiC MOSFET phase-leg modules rated at 1200V/120A
    - 3D printed frame
    - Can operate as dual 3-phase inverter or segmented 3-phase inverter to reduce dc bus capacitor ripple current
  - Designed, built, and tested a 6.6 kW SiC isolation converter with a built-in 2 kW 14V converter using ORNL designed SiC switch phase-leg modules
  - Peak charger system efficiency: 96.5 %, (2 % point improvement over the Si-based counterpart



A SiC traction drive inverter (100 kVA) with an integrated 6.6 kW SiC OBC



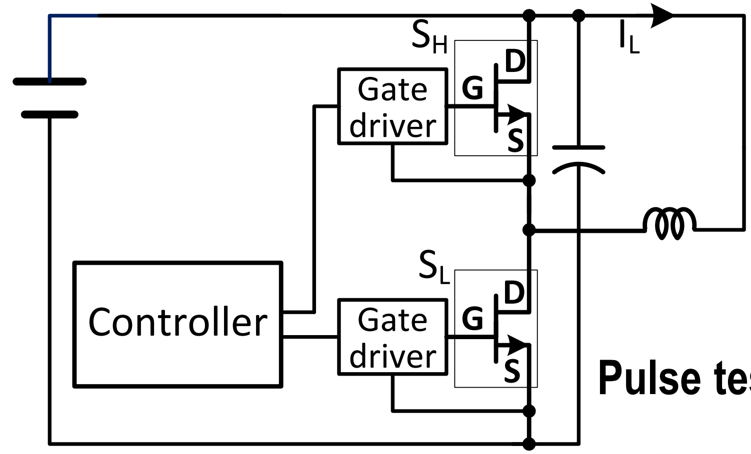
Charger efficiency v.s. output power

Estimated charger comparison

	Power density [kW/L]	Specific Power [kW/kg]	Cost [$/kW]	Efficiency [%]
2012 Nissan LEAF	~0.66	~0.41	~106	85-92
ORNL	~1.3	~0.8	~48	93-96.5

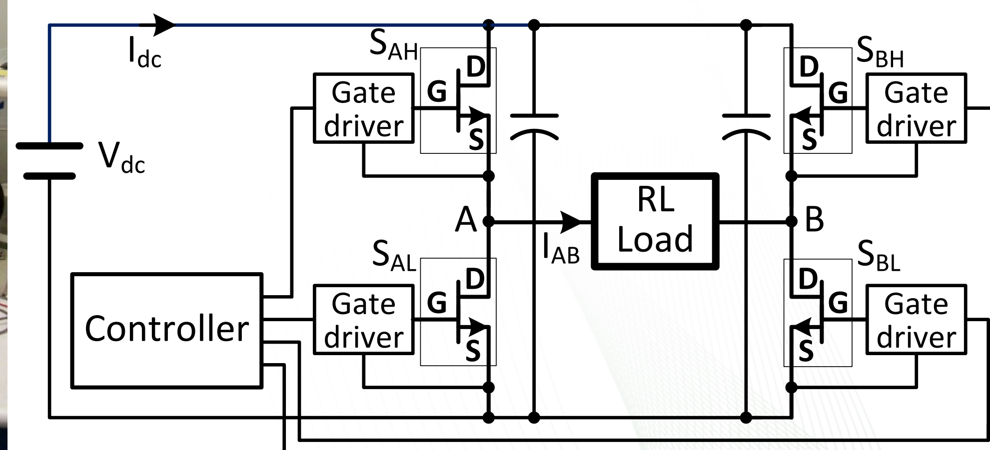
Technical Accomplishments – FY16

- **Conducted evaluation tests of GaN devices manufactured by GaN Systems and collected design data for use in a 6.6 kW GaN isolation converter**
  - **Pulse tests**
  - **H-bridge converter tests**



Pulse test circuit

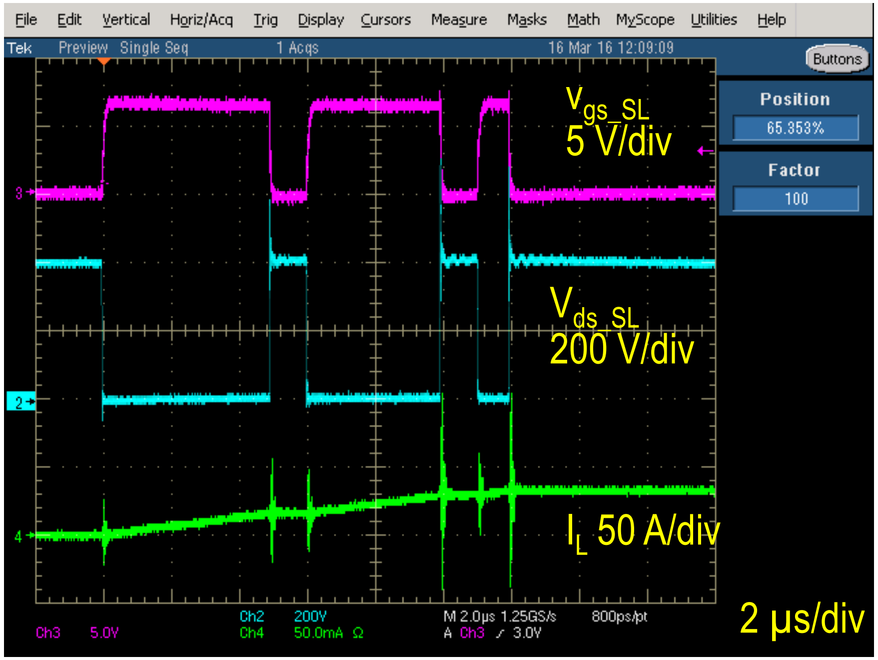
Test setup



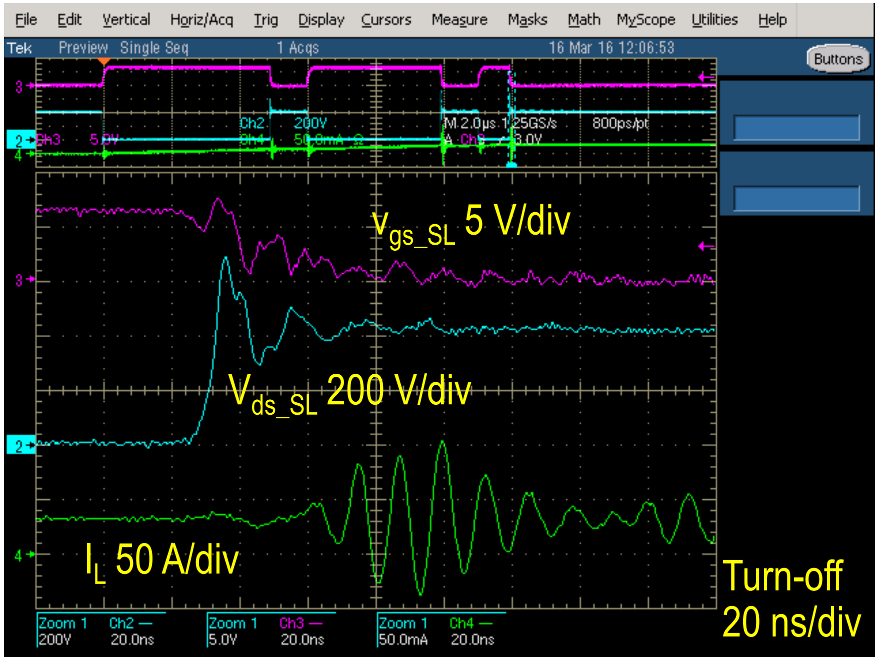
H-bridge converter test circuit

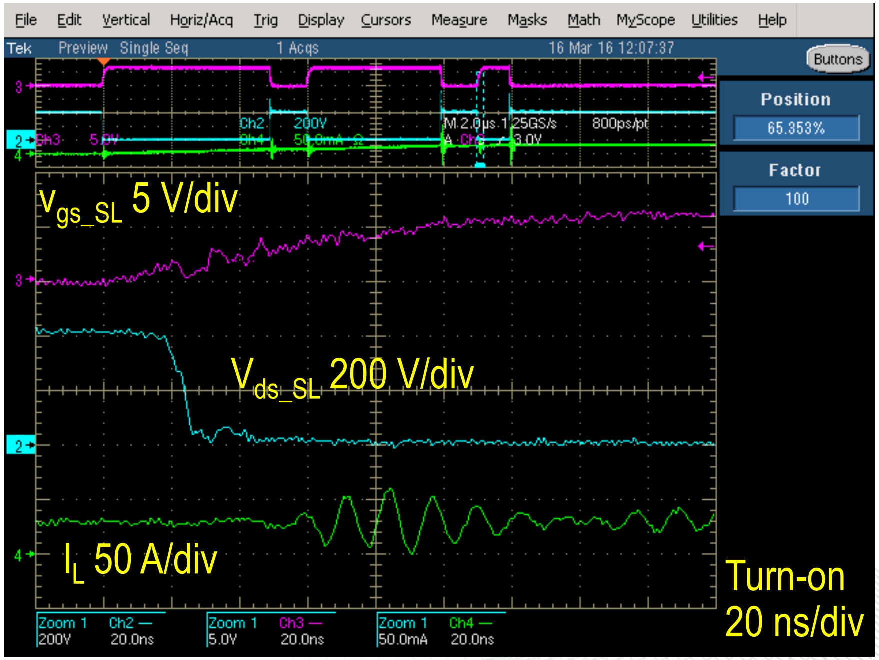
Technical Accomplishments – FY16

- GaN device pulse test results
  - DC bus voltage: 400 V
  - Max. current: 32 A
  - Showing fast switching times of less than 10 ns and low switching losses



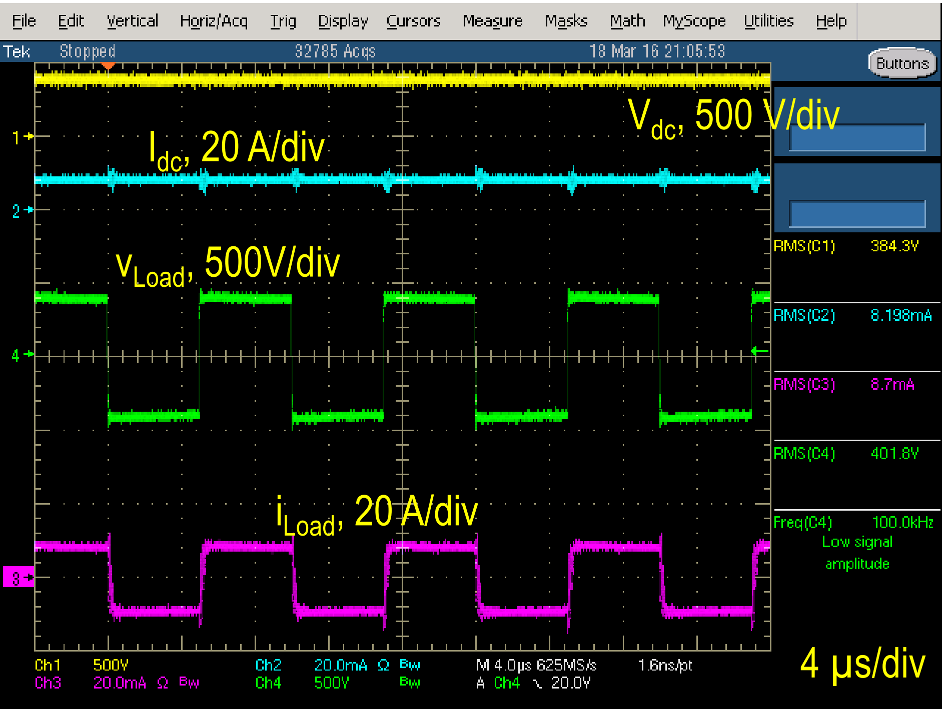
Well suited for high frequency and efficiency dc-dc converter and OBC applications



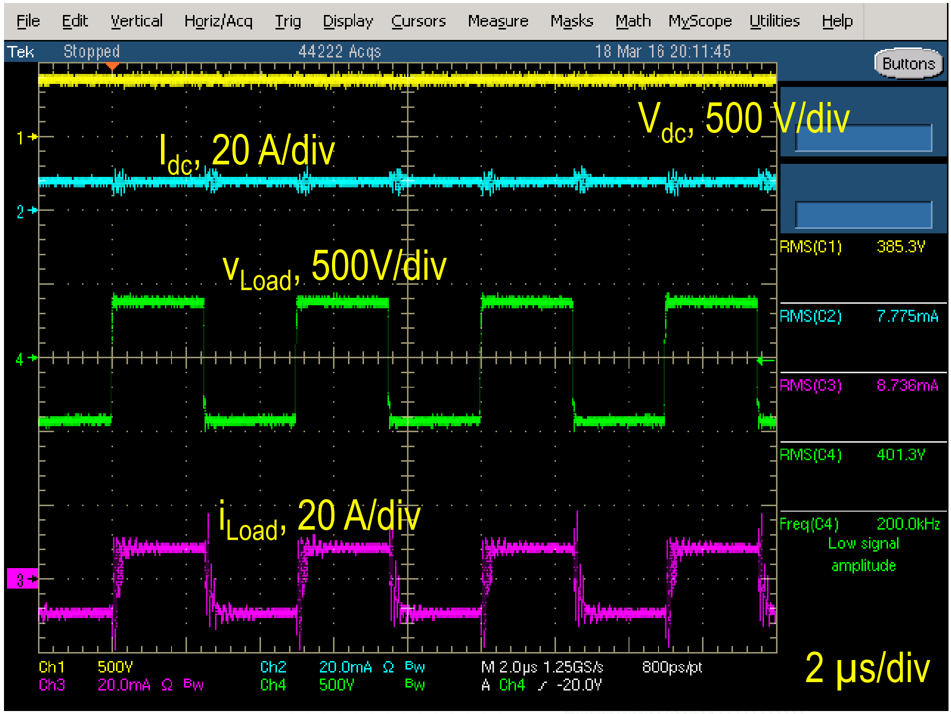


Technical Accomplishments – FY16

- GaN H-bridge converter test results
  - Voltage and current waveforms showing successful operation at 100 kHz and 200 kHz and dc bus voltages of up to 400 V



100 kHz, Load power: 3.2 kW

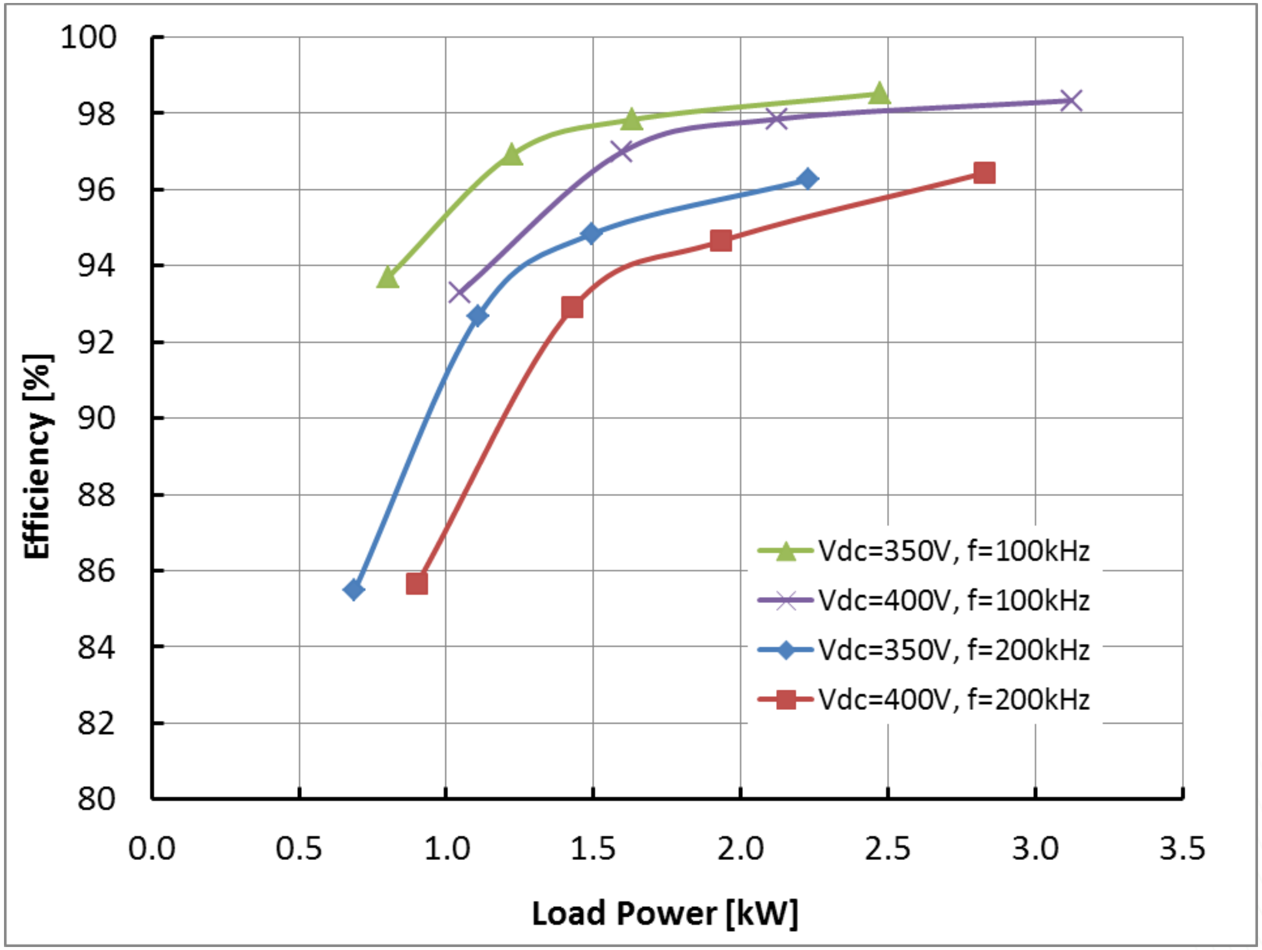


200 kHz, Load power: 2.8 kW

Operating waveforms

Technical Accomplishments – FY16

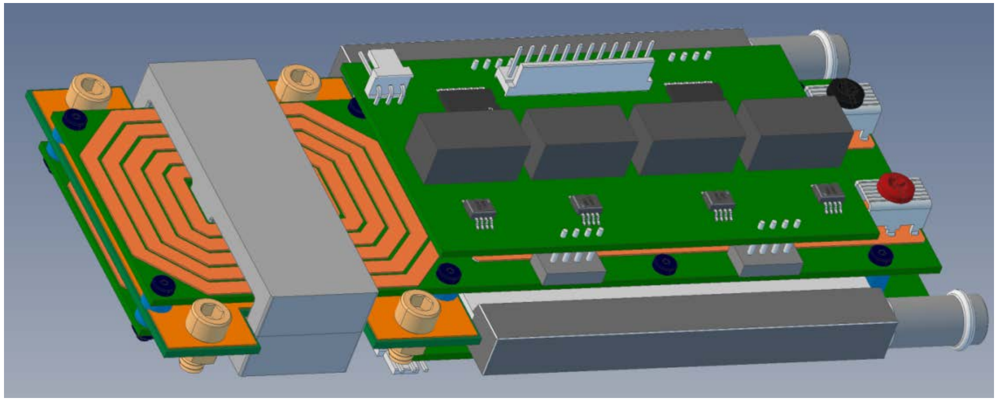
- **GaN H-bridge converter test results**
  - Efficiency v.s. load power at different frequencies and dc bus voltages
  - Indicating our efficiency target of 98 % for isolation converter can be reached at 100 kHz



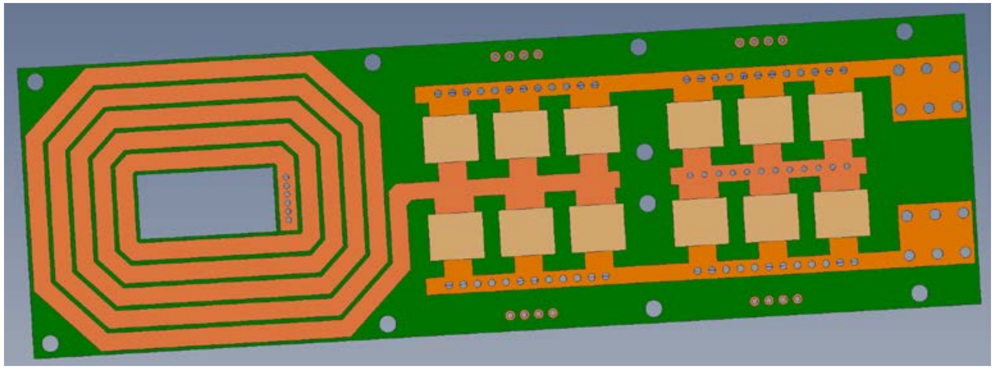
- **Max. efficiencies**
  - 98.5% at 350V and 100 kHz
  - 98.3% at 400V and 100 kHz
  - 96.3% at 350V and 200 kHz
  - 96.4% at 400V and 200 kHz

Technical Accomplishments – FY16

- **Completed design for 6.6 kW GaN isolation converter**
  - Performed layout simulation and iterated designs for the primary and secondary power plane PCB traces to minimize the parasitic inductance using the GaN Systems 650V/47A devices
  - Optimized the power board layout and produced the final design for a 6.6 kW GaN based 3-port isolation converter using the GaN System devices
  - 25 % reduction in foot print and volume compared to the 1st design



Final design for 6.6 kW GaN based 3-port isolation converter (6.6”x4.2”x1.8”)

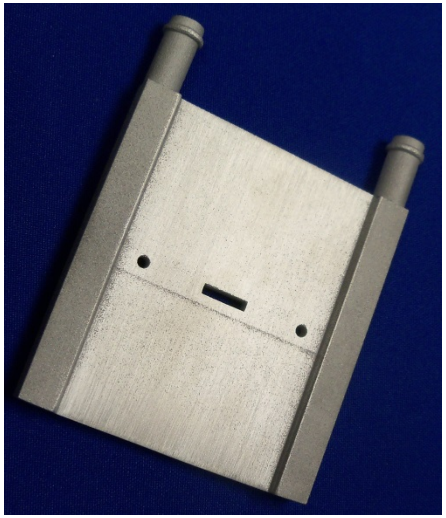


Final design for a 6.6 kW GaN based 3-port isolation converter: PCB for planar transformer winding and GaN power board

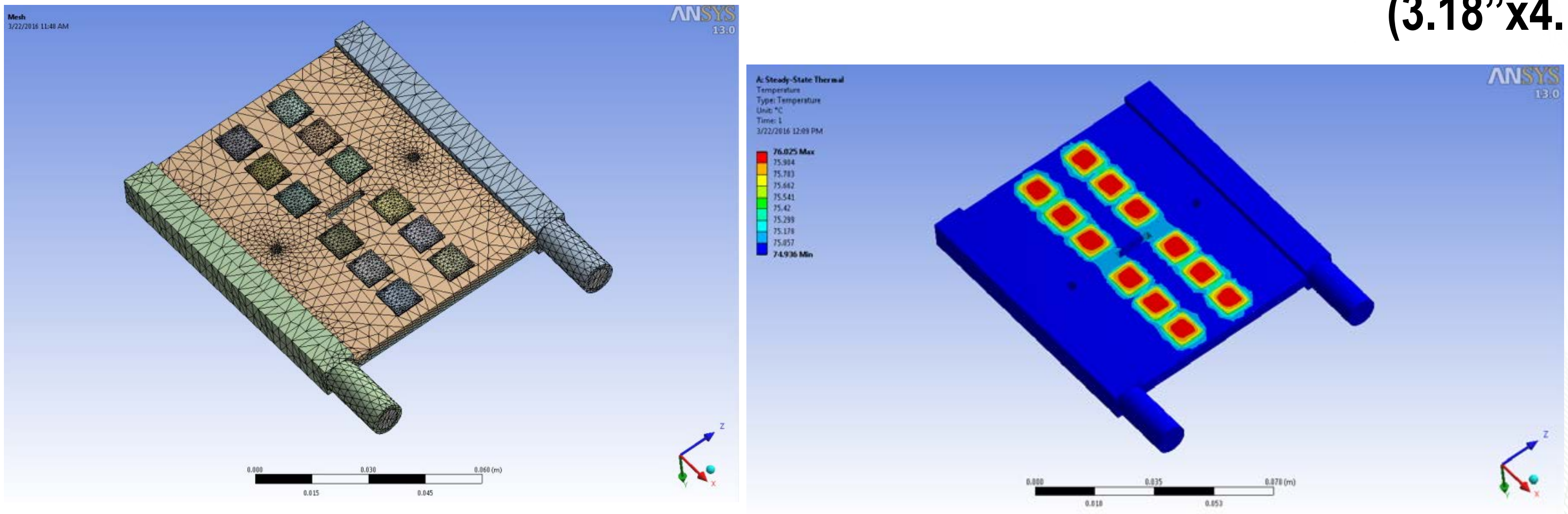
Estimated converter efficiency: 98.2%, exceeding our target of 98 %

Technical Accomplishments – FY16

- **Designed and built an aluminum pin fin cold plate for use in the 6.6 kW GaN isolation converter**
  - Used 3D printing to facilitate the fabrication of a thin (4 mm thick) pin fin cold plate with fine geometries
  - Performed initial finite element thermal analysis and results indicate satisfactory cooling performance (NREL will confirm FEA results)



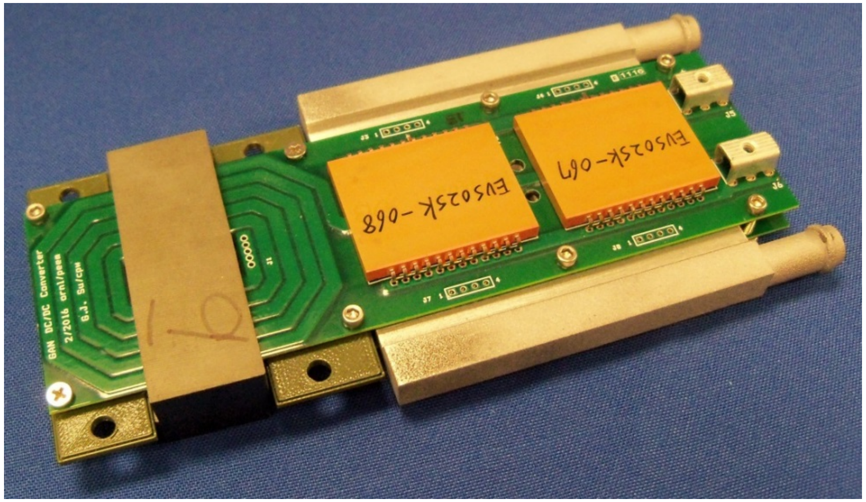
3D printed aluminum pin fin cold plate (3.18”x4.18”x0.375”)



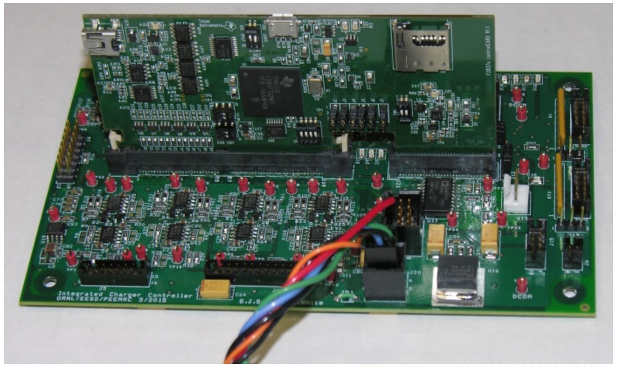
Finite element analysis results

Technical Accomplishments – FY16

- Progress in fabrication of a 6.6 kW GaN isolation converter
  - Completed PCB design, procured and received boards for transformer winding and power plane for mounting the GaN switches
  - Completed gate drive circuit and PCB design, with emphasis on minimizing gate loop inductance and easy tuning of turn-on and turn-off speeds
  - Working with a magnetic vendor, designed and fabricated customized ferrite cores for the planar transformer
  - Designed and built a DSP control board using the new TI dual-core chip TMS320F28377D for implementing high-speed high-resolution PWM control loops



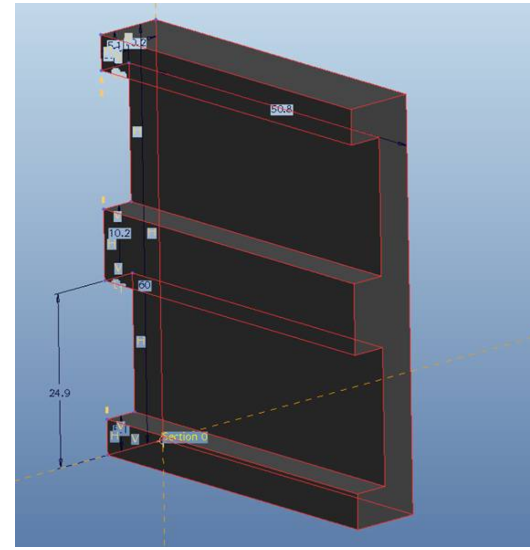
6.6 kW GaN isolation converter



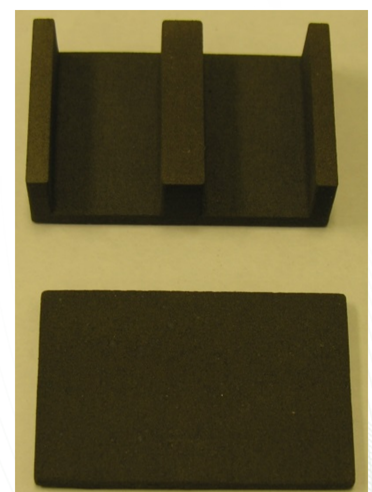
DSP board using the new TI dual-core chip TMS320F28377D

Technical Accomplishments – FY16

- Working with Aegis Technology, generated a transformer core design using their low-loss nano-composite magnetic powder material and printed an E-core at ORNL's manufacturing demonstration facility.
- Fabricated an inductor using the printed core and performed characterization tests
  – Inductance increased less than 2 times compared to the air core; about 100 times increase was measured with a similar size commercial ferrite core
  – Insignificant change in resistance with or without the printed core; 4 to 47 times increase were observed with the commercial core
- More work is needed on printing processes



ORNL Core design



ORNL printed core set

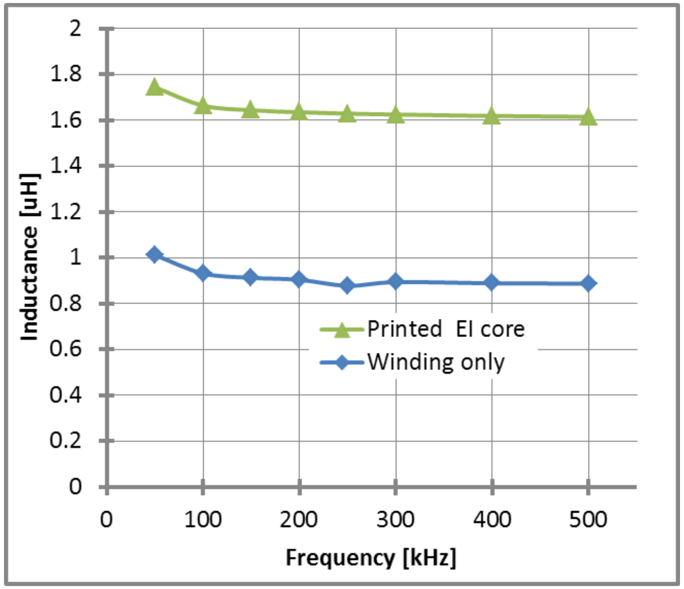
Commercial ferrite core

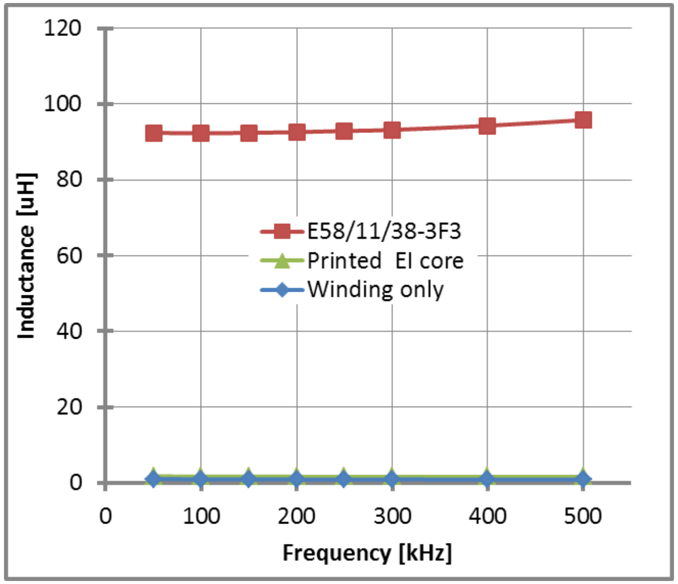
Inductor for characterization

Technical Accomplishments – FY16

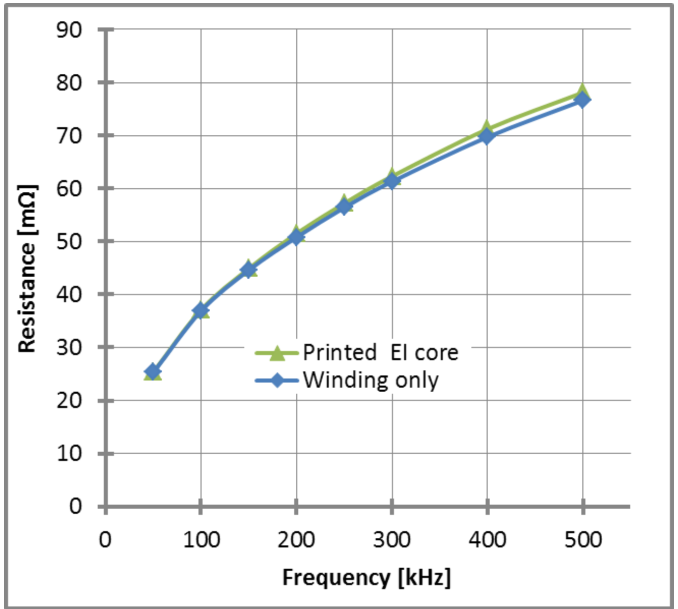
- **Measured inductance and resistance of the inductor using the printed core**

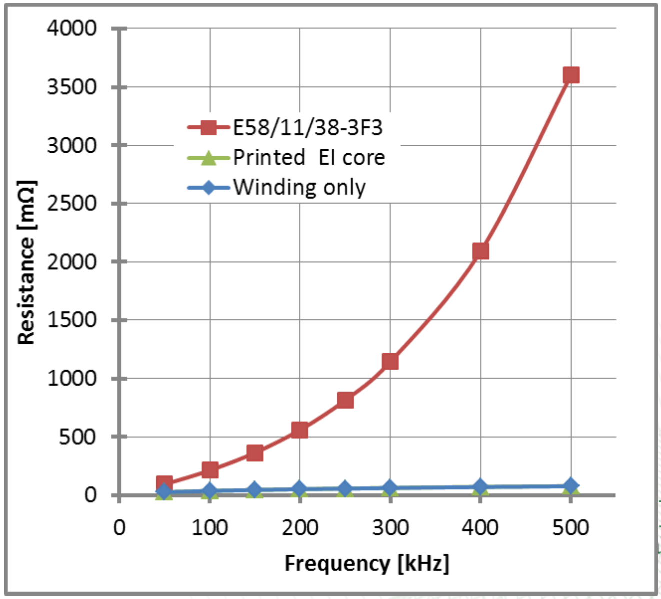
Inductance





Resistance





Responses to Previous Year Reviewers' Comments

- One reviewer commented: OBC uses electric machines in charging circuit and machine inductance varies over a wide range depending upon number of poles and types of electric machine used. High-pole count PM machines are getting very popular due to their smaller weight and size and they have much smaller leakage inductance than induction machines. Response: For machines of very low inductance, an additional inductor may be needed for Si-IGBT based traction drive inverters due to their low switching frequency. This should not be an issue for SiC or GaN based traction drive inverters. In addition, interleaved switching among the three phase legs can be used to further reduce the requirement for machine inductance. Moreover, systems with dual motors which have become a popular choice for PHEVs or a boost converter provide higher inductance.

- One reviewer recommended: an input filter between the 240/120 AC system and the rectifier should be included; and similarly, an output filter between the isolated DC-DC converter and the battery pack. The input filter could possibly be motor windings. Response: We agree a small LC output filter may be needed for meeting battery charging current requirements. As for the input filter, the motor inductance should be enough in most cases for the reasons given in the above response.

- One reviewer said: the system appeared to have a high efficiency, but was concerned with the overall size of the system, and so recommended a focus on downsizing the package be considered in the future. Response: Since the traction drive inverter and motor are used as the front ac-dc converter for the charger and the 14V accessory dc-dc converter is integrated into the charger, the integrated system should be much smaller and less costly than current systems with standalone chargers and 14V accessory dc-dc converters. That said, system packaging is still an important area that deserves much attention.

Collaboration and Coordination with Other Institutions

- GaN Systems — input on gate driver design and GaN devices
- ROHM — SiC power modules and gate drive chips
- Aegis Technology Inc. — light-weight, low loss nano-magnetic materials
- Ferroxcube USA — input on design and fabrication of high frequency inductors and transformers using soft ferrites
- NREL — input on thermal management design

Remaining Challenges and Barriers

- Challenges
  – Achieving high efficiency at low cost
- Barriers
  – Availability of low cost WBG devices (Si-substrate based GaN devices have potential to provide lower cost solutions over SiC devices)

Proposed Future Work

- **Remainder of FY16**
  – Complete the build and test of a 6.6 kW GaN isolation converter
  – Integrate the 6.6 kW all-GaN isolation converter with a SiC traction drive for an all-WBG OBC and test and characterize the integrated OBC

Summary

- **Relevance:** This project is targeted toward leapfrogging the present Si based charger technology to address charger and converter cost, weight, volume, and efficiency targets.
- **Approach:** The approach being pursued is to overcome the limitations of present semiconductor and magnetic materials with WBG devices and advanced magnetic materials to significantly increase power density, specific power and efficiency at lower cost, and to further reduce cost by using novel integrated topologies and control strategies.
- **Collaborations:** Collaboration with several industry stakeholders are being used to maximize the impact of this work.
- **Technical Accomplishments:**
  - Conducted tests of GaN Systems 650 V GaN switches and collected data for use in designing a 6.6 kW GaN isolation converter.
  - Completed design for a 6.6 kW GaN isolation converter using the GaN Systems 650 V/47 A devices and a 3D printed aluminum cold plate.
  - Progress in fabrication of a 6.6 kW GaN isolation converter.
  - Designed and fabricated nano-composite magnetic cores using 3D printing and performed characterization tests in an inductor.
- **Future Work:** Build and test 6.6 KW GaN based integrated chargers